Neutrino Masses

and

Physics beyond the Standard Model

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CASE WESTERN RESERVE UNIVERSITY EST. 1826

think beyond the possible™

NuTheories: Beyond the 3 × 3 Paradigm at Current and Near-Future Facilities, Univ. of Pittsburgh, Nov 2018

Neutrinos are Massive !

What is the origin of Neutrino Masses ?

How do we test the theory of Neutrino Masses ?

Massive Neutrinos

NuFit Collaboration

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

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Massive Neutrinos

- Dirac Fermions — *B-L Conservation !*

$$-\mathcal{L}_D = Y_\nu^D \ \bar{\ell}_L i\sigma_2 H^* \nu_R + \text{h.c.}$$

- Majorana Fermions — *B-L Violation !*

Many Ideas !

Dirac Neutrinos

B-L Conservation !

$$-\mathcal{L}_D = Y_\nu^D \; \bar{\ell}_L i\sigma_2 H^* \nu_R + \text{h.c.}$$

$Y_\nu^D \lesssim 10^{-12}$ ⇒ $M_\nu \lesssim 0.1 \text{ eV}$

$3\nu_R$ ⇒ $U(1)_{B-L}$ Local Anomaly Free Symmetry

a) Unbroken B-L: Stueckelberg Mechanism — Feldman, P.F.P., Nath

b) Broken B-L: $S_{BL} \sim (1,1,0,n_{BL}), |n_{BL}| > 2.$

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(Minkowski, Mohapatra, Senjanovic, Glashow, Yanagida, Gell-Mann, Ramond, Slansky)

Majorana Neutrinos

$$-\mathcal{L}_M = Y_\nu^D \ \bar{\ell}_L i\sigma_2 H^* \nu_R + \frac{1}{2} M_R \nu_R^T C \nu_R + \text{h.c.}$$ (Canonical Seesaw)

$$\Rightarrow \quad M_\nu = m_D M_R^{-1} m_D^T$$

if $m_D \sim 10^2 \text{GeV}$ $\Rightarrow$ $M_R \lesssim 10^{14-15} \text{GeV}$

(Seesaw Scale)

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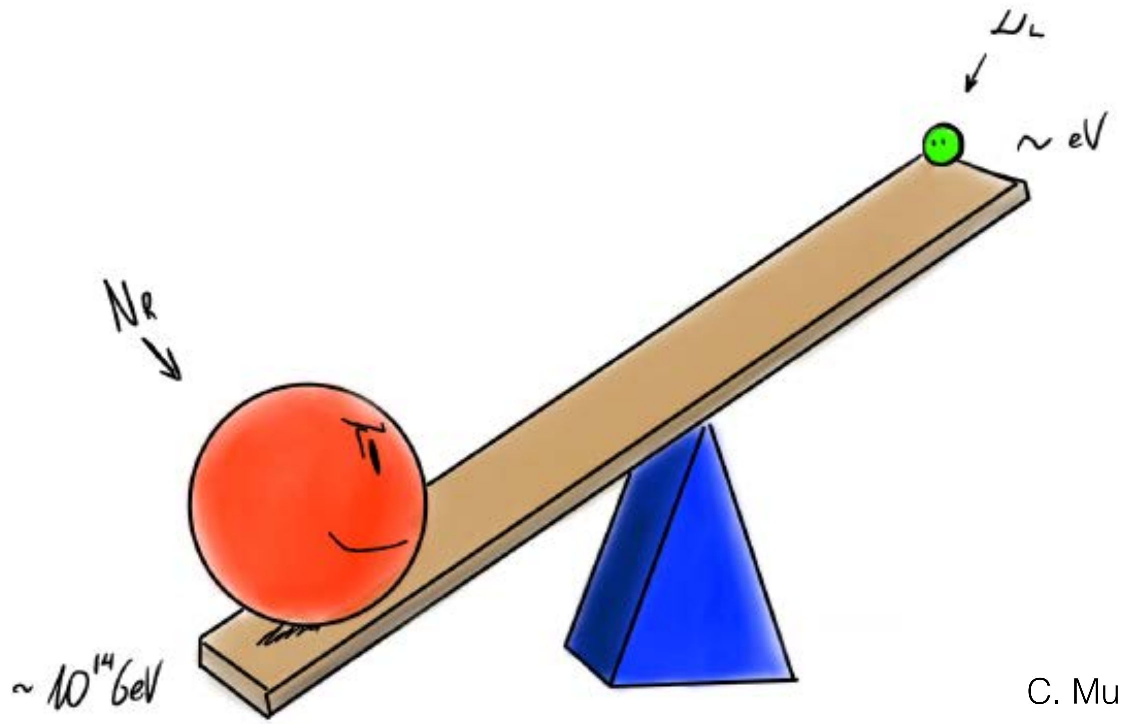
The Canonical Seesaw

- In general, the upper bound for the $B-L$ breaking scale is the canonical seesaw scale, i.e. $v_{B-L} \lesssim 10^{14}$ GeV.



C. Murgui

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Simple Scenarios for Neutrino Masses

- Type I Seesaw
- Type II Seesaw
- Type III Seesaw
- Zee Model
- Colored Seesaw
- Witten's Mechanism

... Others !

...

...

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Gauge Theories for Neutrino Masses

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The Simplest Theory is based on Local B-L

$$U(1)_{B-L}$$

$$-\mathcal{L}_{\nu}^{I} = Y_{\nu}\, \overline{\ell_L} i\sigma_2 H^* \nu_R + \lambda_R\, \nu_R^T C \nu_R S_{BL} + \text{h.c.},$$

$$S_{BL} \sim (1,1,0,2)$$

$$M_{\nu} = m_D M_R^{-1} m_D^T$$

What is the B-L Seesaw Scale ? ⇒ $M_R \lesssim 10^{14-15}\text{GeV}$

How do we test this theory ?

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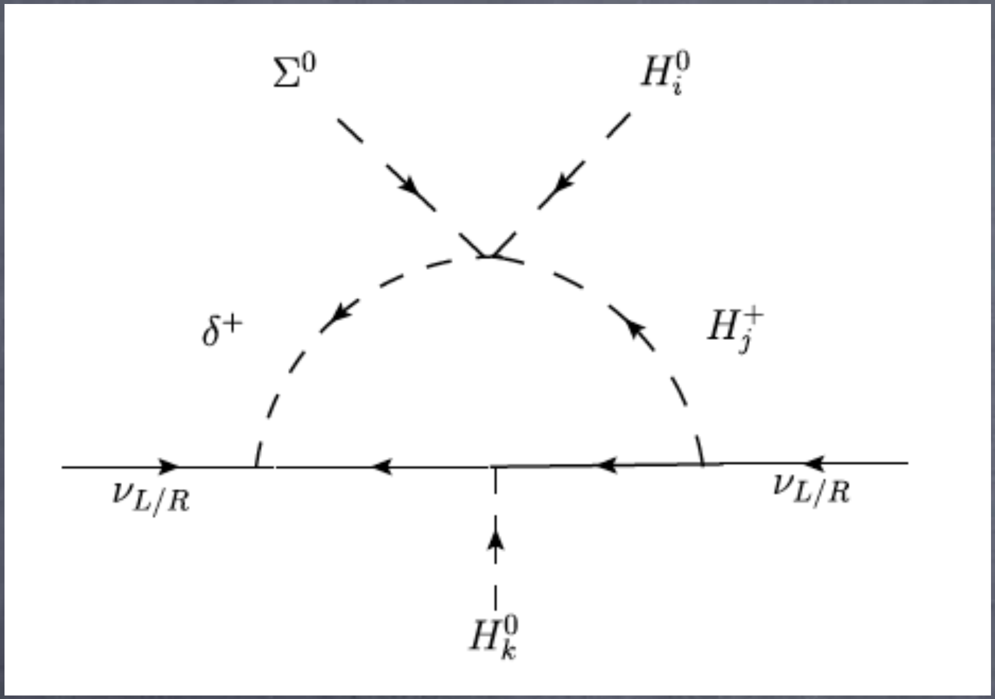
P. F. P., C. Murgui, Phys. Lett. B777 (2018) 381

B-L Zee Model



Simplest realization of the Zee mechanism in a B-L Theory!

$\delta^+ \sim (1,1,1,2)$ $\quad$ $\Sigma \sim (1,3,0,2)$

B-L Radiative Seesaw

P. F. P., C. Murgui, Phys. Lett. B777 (2018) 381

$$-\mathcal{L}_\nu^{\rm RS} = \lambda_L \ell_L^T C i\sigma_2 \ell_L \delta^+ + \lambda_R \nu_R^T C e_R \delta^+ + \lambda_{ij} H_i^T i\sigma_2 \Sigma H_j \delta^- + Y_e^i \bar{\ell}_L H_i e_R + Y_\nu^i \bar{\ell}_L i\sigma_2 H_i^* \nu_R + \text{h.c.},$$

$$\mathcal{M}_\nu = \begin{pmatrix} M_\nu^L & M_\nu^D \\ (M_\nu^D)^T & M_\nu^R \end{pmatrix}$$

$$(M_\nu^L)^{\alpha\gamma} = \frac{1}{8\pi^2} \sum_\beta \lambda_L^{\alpha\beta} m_{e_\beta} \sum_i \text{Log}\left(\frac{m_{h_i}^2}{m_{e_\beta}^2}\right) \times (Y_{e1}^{\dagger\,\beta\gamma} V_{1i}^* + Y_{e2}^{\dagger\,\beta\gamma} V_{2i}^*) V_{5i} + \alpha \leftrightarrow \gamma$$

$$(M_\nu^R)^{\alpha\gamma} = \frac{1}{(4\pi)^2} \sum_\beta \lambda_R^{\alpha\beta} m_{e_\beta} \sum_i \text{Log}\left(\frac{m_{h_i}^2}{m_{e_\beta}^2}\right) \times (Y_{\nu 1}^{\beta\gamma} V_{1i}^* + Y_{\nu 2}^{\beta\gamma} V_{2i}^*) V_{5i} + \alpha \leftrightarrow \gamma$$

a) One can have very light sterile neutrinos

$$\left(M_\nu^R << M_\nu^L\right)$$

b) One could have large contributions to LFV processes

Can we realize Seesaw at the Low Scale?

Dark Matter and Seesaw Scale

P. F. P., C. Murgui, Phys.Rev. D98 (2018) 055008

Seesaw Scale and Dark Matter

Neutrino Masses ⟷ $U(1)_{B-L}$ ⟷ Dark Matter

$$\mathcal{L}_\nu^{DM} \supset -\frac{1}{4} F_{\mu\nu}^{BL} F_{\alpha\beta}^{BL} g^{\alpha\mu} g^{\beta\nu} + i\overline{\chi}_L \gamma^\mu D_\mu \chi_L + i\overline{\chi}_R \gamma^\mu D_\mu \chi_R + (D_\mu S_{BL})^\dagger (D^\mu S_{BL})$$
$$- \left(Y_\nu\, \bar{\ell}_L i\sigma_2 H^* \nu_R \;+\; \lambda_R\, \nu_R^T C \nu_R S_{BL} + M_\chi \bar{\chi}_L \chi_R + \text{h.c.}\right),$$

$$M_R = \sqrt{2}\lambda_R v_{BL} \qquad M_{Z_{BL}} = 2 g_{BL} v_{BL}$$

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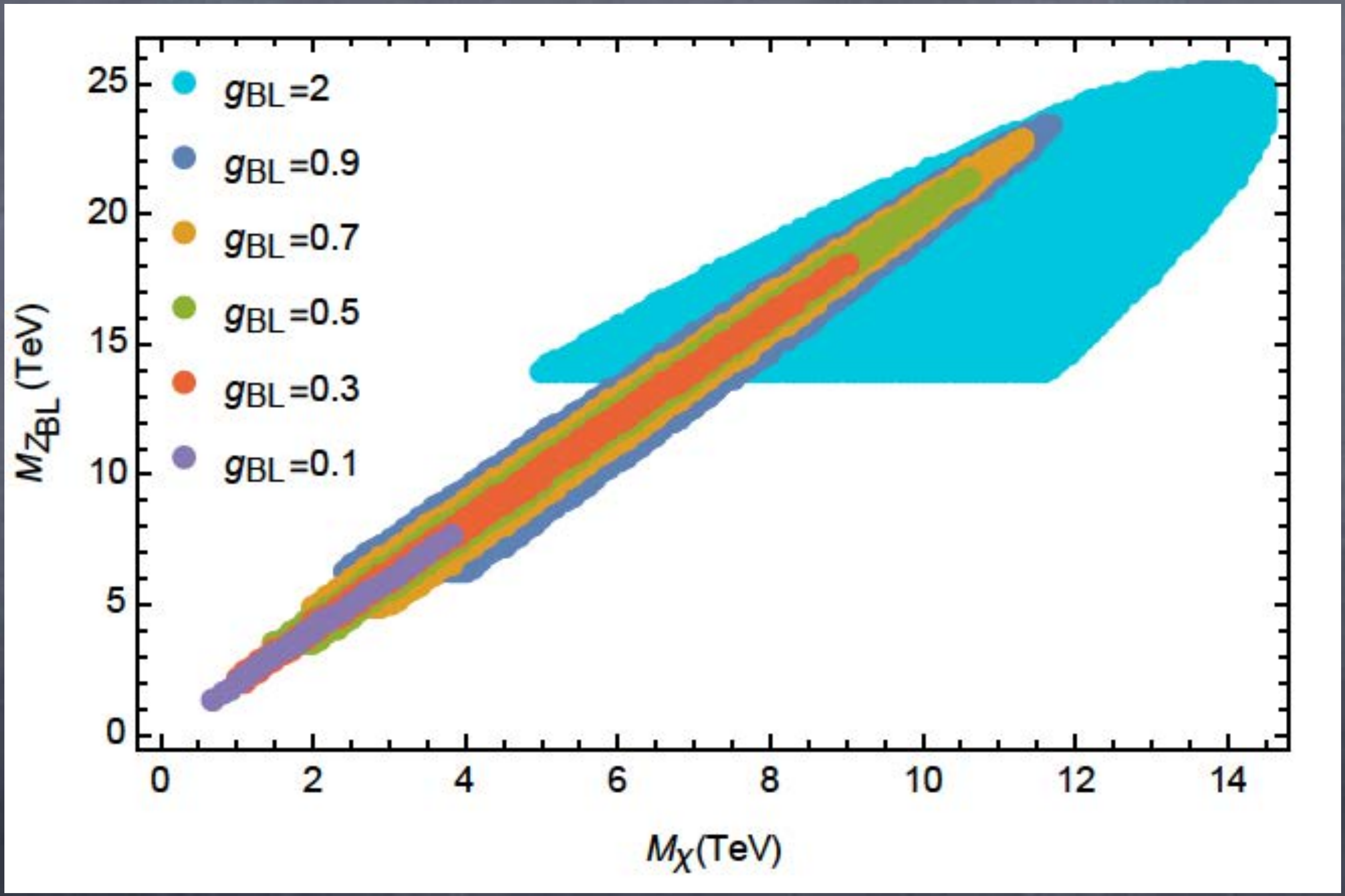
Seesaw Scale and Dark Matter

$n = 1/3$ when $\Omega_{DM}h^2 \leq 0.1199 \pm 0.0027$



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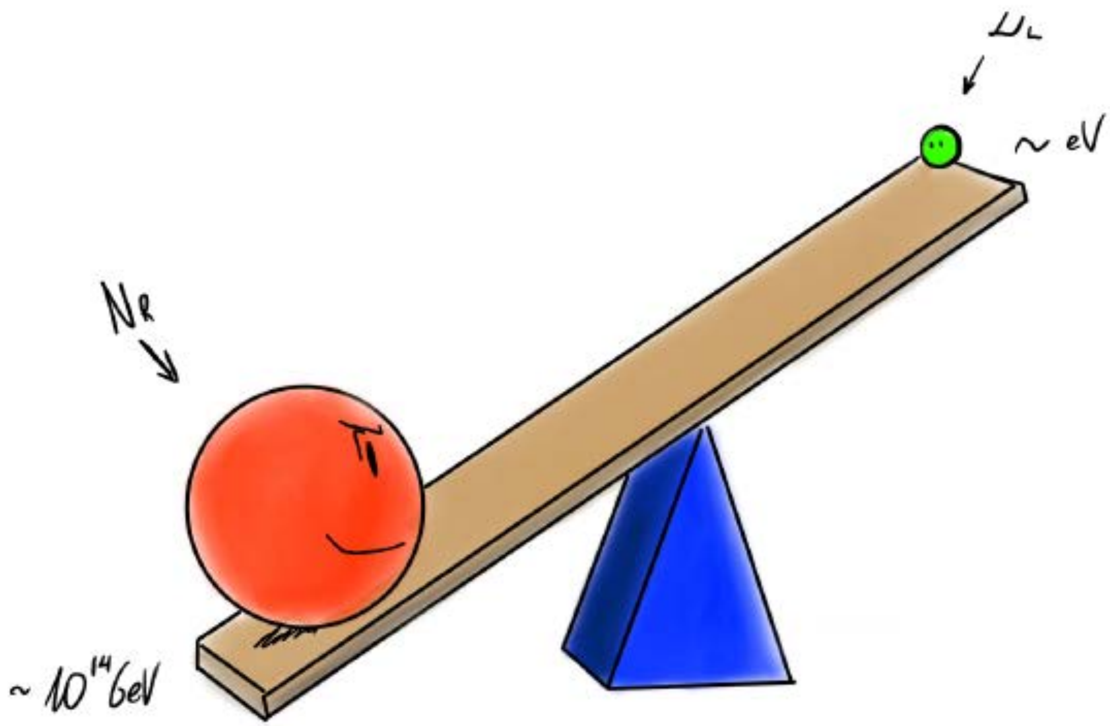
Seesaw Scale and Dark Matter

The Canonical Seesaw

- In general, the upper bound for the $B-L$ breaking scale is the canonical seesaw scale, i.e. $v_{B-L} \lesssim 10^{14}$ GeV.



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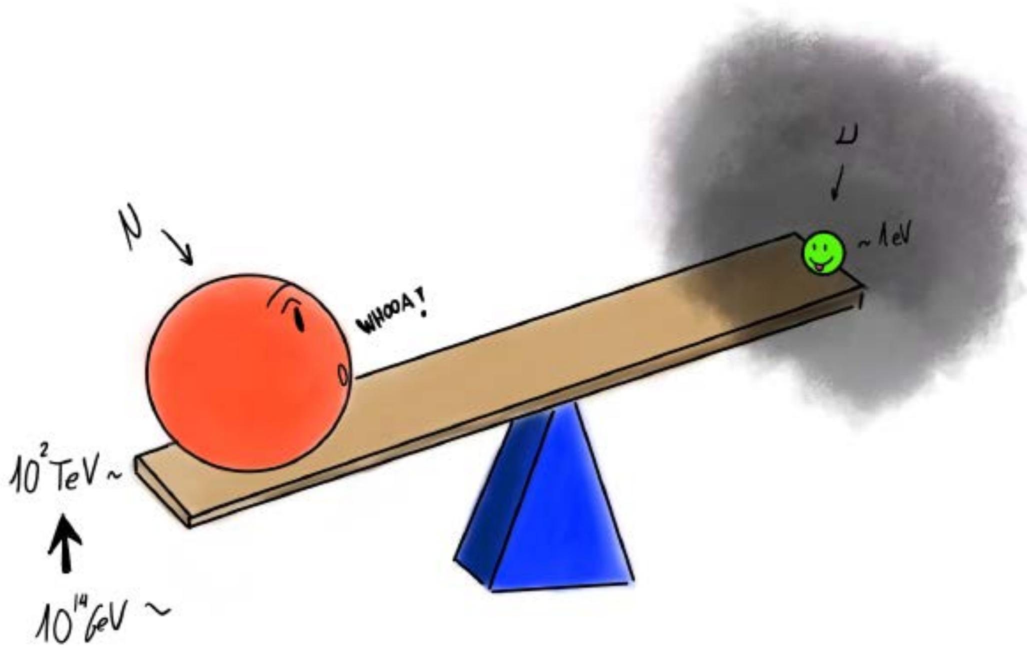
Seesaw Scale and Dark Matter

The ~~Canonical~~ "Dark"Seesaw

- The presence of Dark Matter in the game lowers considerably the upper bound to $v_{B-L} \lesssim 200$ TeV.



- Hope to see signals in a near future!!!

SALE
SAVE UP TO 9 ORDERS OF MAGNITUDE

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P. F. P., C. Murgui, Phys.Rev. D98 (2018) 055008

Seesaw Scale and Dark Matter

The upper bound on B-L Seesaw Scale is in the multi-TeV region

Therefore there is a hope to test the origin of neutrinos masses at Colliders !

Signatures at LHC

$$pp \to Z_{BL}^{*} \to N_i N_i \to e_j^{\pm} W^{\mp} e_k^{\pm} W^{\mp} \to e_j^{\pm} e_k^{\pm} 4j.$$

P. F. P., T. Han, T. Li

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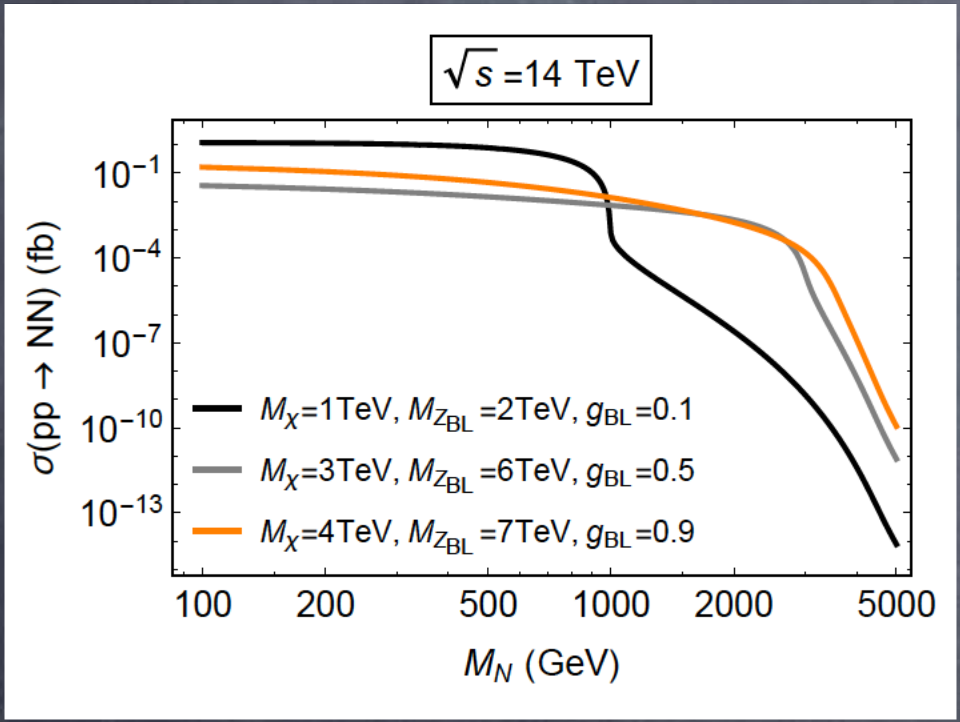
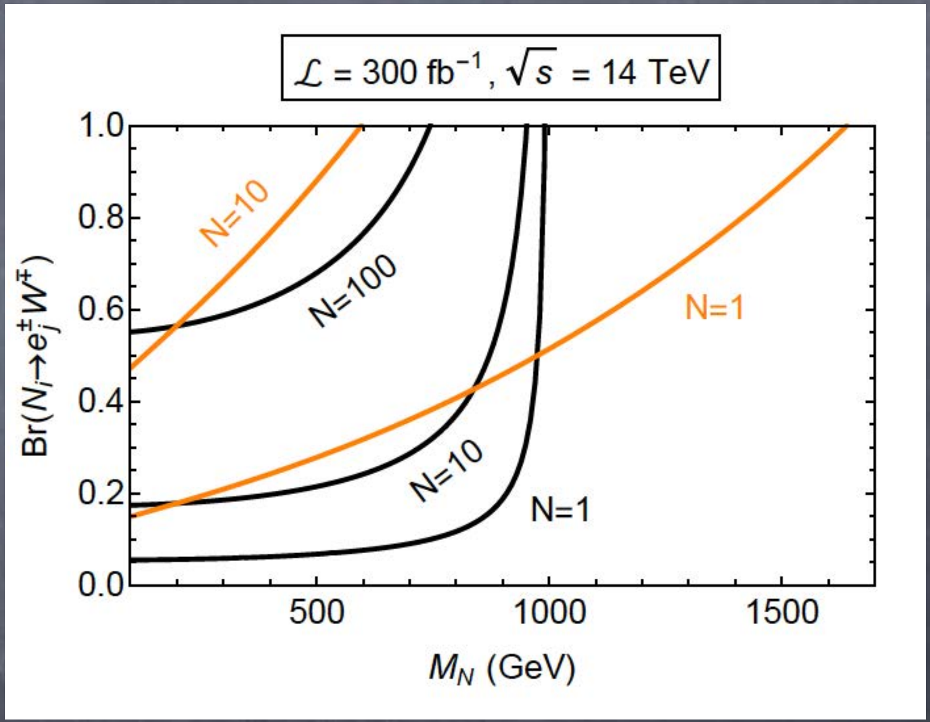
Testability at the LHC

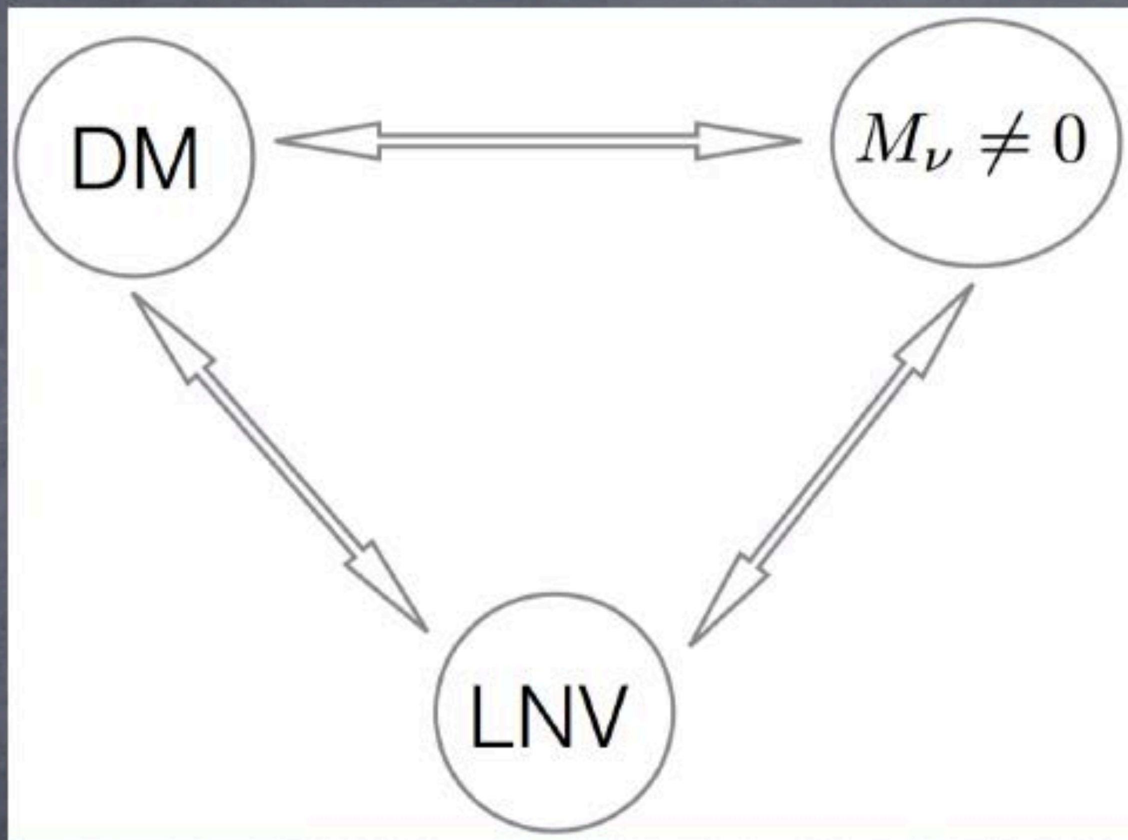
$$pp \to Z^*_{BL} \to N_i N_i \to e^\pm_j W^\mp e^\pm_k W^\mp \to e^\pm_j e^\pm_k 4j.$$





The LHC could see these events in the near future !

P. F. P., C. Murgui, Phys.Rev. D98 (2018) 055008



One can expect lepton number violating and DM signatures at the LHC

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Supersymmetry and Seesaw Scale

MSSM Interactions

$$\mathcal{W}_{RpC} = Y_u Q H_u u^c + Y_d Q H_d d^c + Y_e L H_d e^c + \mu H_u H_d$$

$$\mathcal{W}_{RpV} = \epsilon L H_u + \lambda L L e^c + \lambda^{'} Q L d^c + \lambda^{''} u^c d^c d^c$$

$$R = (-1)^{3(B-L)+2S} = (-1)^{2S} M$$

LSP $\tilde{\chi}^0_1 = \left(\tilde{B}, \tilde{W}, \tilde{H}^0_u, \tilde{H}^0_d\right)$ → **Cold Dark Matter !**

if R-parity is conserved !

$$\mathcal{W}_{RpV} = \epsilon L H_u + \lambda L L e^c + \lambda^{'} Q L d^c + \lambda^{''} u^c d^c d^c$$

What is the origin of the lepton and baryon number violating interactions in the MSSM?

Matter-Parity: $M = (-1)^{3(B-L)}$

$B - L \longleftrightarrow M$

V. Barger, P. Fileviez Perez, S. Spinner, Phys. Rev. Lett.102:181802,2009

Minimal B-L Theory for R-Parity Violation

$$G_{B-L} = SU(3)_C \bigotimes SU(2)_L \bigotimes U(1)_Y \bigotimes U(1)_{B-L}$$

Matter:

$\hat{Q} \sim (3, 2, 1/3, 1/3)$ $\quad$ $\hat{L} \sim (1, 2, -1, -1)$

$\hat{u}^c \sim (\bar{3}, 1, -4/3, -1/3)$ $\quad$ $\hat{e}^c \sim (1, 1, 2, 1)$

$\hat{d}^c \sim (\bar{3}, 1, 2/3, -1/3)$

→ $\hat{\nu}^c \sim (1, 1, 0, 1)$ **(for anomaly cancellation)**

Symmetry Breaking and SRpV

$$G_{B-L} \Rightarrow G_{SM} \qquad \left\{ \langle \tilde{\nu}^c \rangle = \frac{v_R}{\sqrt{2}} \right\}$$

$$\left. \begin{aligned} \langle H_u^0 \rangle &= \frac{v_u}{\sqrt{2}} \\ \langle H_d^0 \rangle &= \frac{v_d}{\sqrt{2}} \end{aligned} \right] \quad G_{SM} \Rightarrow SU(3)_C \otimes U(1)_{em}$$

$$\langle \tilde{\nu} \rangle = \frac{v_L}{\sqrt{2}} \neq 0$$

New Theory with R-parity violation !

The Minimal B-L Model predicts

- R-parity must be spontaneously broken !

- The B-L and R-parity breaking scales are defined by the SUSY scale.

- Lepton number violating signals at the LHC !

if SUSY is realized at the multi-TeV Scale

P.F.P., Spinner

Scalar Potential and Symmetry Breaking

$$\mathcal{W}_{B-L} = \mathcal{W}_{RpC} + Y_\nu L H_u \nu^c$$

$$V_{soft} \supset M^2_{\tilde{N}^c} |\tilde{\nu}^c|^2 + \left(A_\nu \tilde{L} H_u \tilde{\nu}^c \ + \ \text{h.c.} \right)$$

$$\langle V_D \rangle = \frac{1}{32} \left[g_2^2 \left(v_u^2 - v_d^2 - v_L^2 \right)^2 + g_1^2 \left(v_u^2 - v_d^2 - v_L^2 \right)^2 \ + \ g_{BL}^2 \left(v_R^2 - v_L^2 \right)^2 \right],$$

$$v_R = \sqrt{\frac{-8 M^2_{\tilde{N}^c}}{g^2_{BL}}} \quad \left(M^2_{\tilde{N}^c} < 0 \right) \quad |M^2_{\tilde{N}^c}| \sim M^2_{SUSY}$$

The B-L and R-parity breaking scales are defined by the SUSY scale !

The mass matrix for all light neutrinos:

Barger, P.F.P., Spinner'10

Mohapatra'86;
Ghosh, Senjanovic, Zhang'10

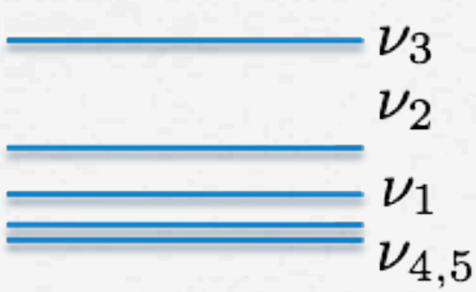
$$(\nu_e, \nu_\mu, \nu_\tau, \nu_e^c, \nu_\mu^c)$$

$$M_\nu = \begin{pmatrix} A v_L^i v_L^j + B(Y_\nu^{i3} v_L^j + Y_\nu^{j3} v_L^i) + C Y_\nu^{i3} Y_\nu^{j3} & Y_\nu^{i\beta} v_u/\sqrt{2} \\ Y_\nu^{\alpha j} v_u/\sqrt{2} & 0_{2\times 2} \end{pmatrix}$$

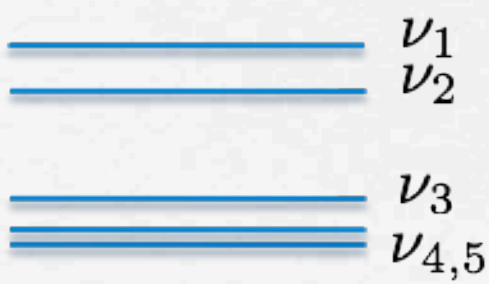
$\left(M_{\nu_\tau^c} \sim M_{SUSY} \right)$

Possible spectra:

NH



IH



The theory predicts two light sterile neutrinos !

Unification and Seesaw Scale

Georgi-Glashow Model

Georgi, Glashow, Phys.Rev.Lett.32:438-441,1974

$$G_{SM} = SU(3) \otimes SU(2) \otimes U(1) \subset SU(5)$$

$$\alpha_3 \qquad \alpha_2 \qquad \alpha_1 \quad \longrightarrow \quad \alpha_5$$

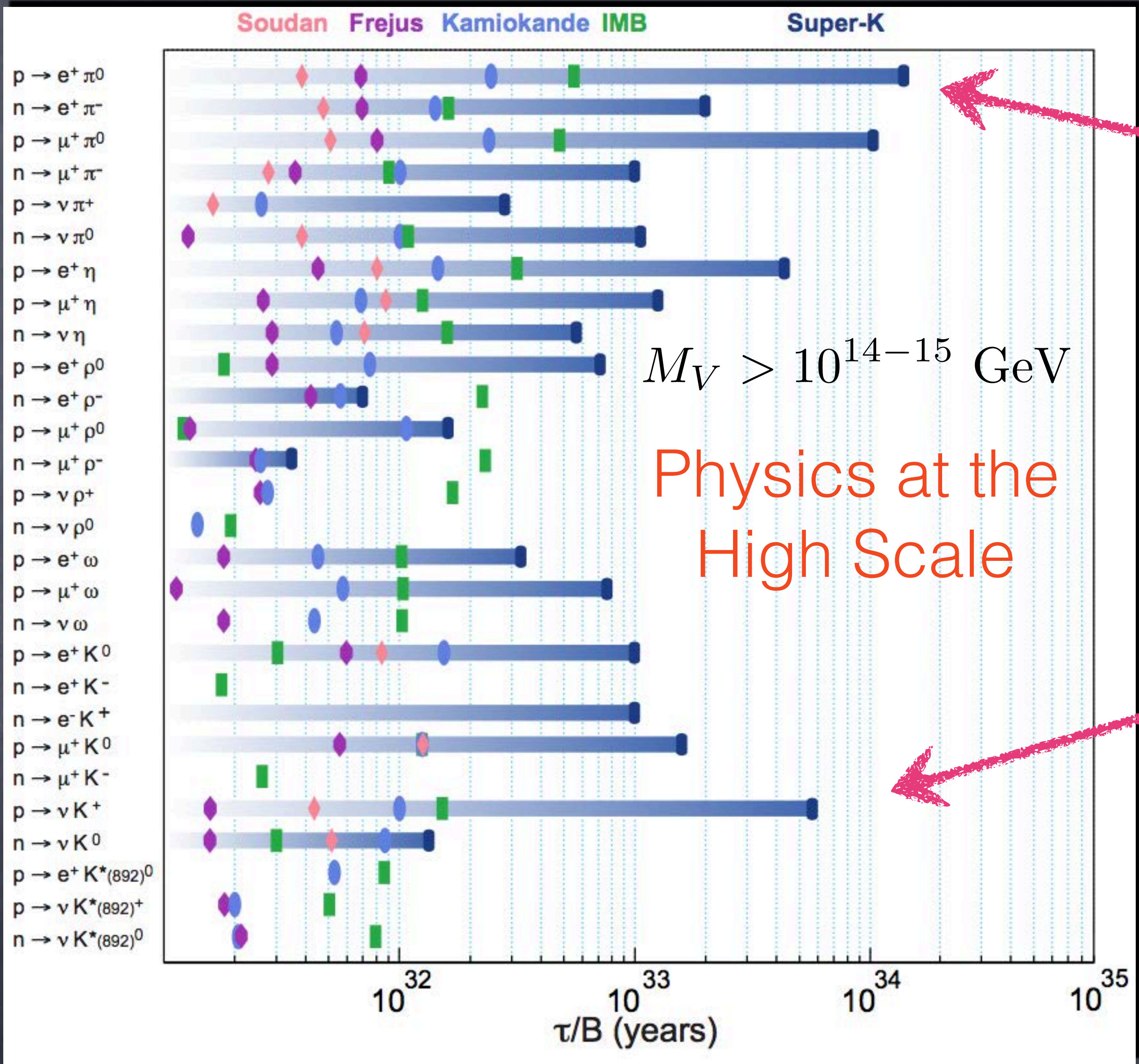
Matter Assignment

$$\bar{\mathbf{5}} = \begin{pmatrix} d_1^C \\ d_2^C \\ d_3^C \\ e \\ -\nu \end{pmatrix}_L \qquad \mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^C & -u_2^C & u_1 & d_1 \\ -u_3^C & 0 & u_1^C & u_2 & u_2 \\ u_2^C & -u_1^C & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^C \\ -d_1 & -d_2 & -d_3 & -e^C & 0 \end{pmatrix}_L$$

Higgs Bosons $\quad 5_H \quad 24_H$

B and L are explicitly broken !

Proton Decay: $\Delta B = 1, \ \Delta L = \text{odd}$



$$M_V > 10^{14-15} \ \text{GeV}$$

Physics at the High Scale

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The Georgi-Glashow Model is ruled out !

- The unification of gauge couplings in disagreement with the values of the couplings at the electroweak scale.

- Wrong relation between charged leptons and down quark masses.

- Neutrino are massless as in the SM.

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P. F. P., A. Gross, C. Murgui, Phys.Rev. D98 (2018) 035032

Realistic SU(5) Grand Unified Theory

SM Matter:

$$\bar{5} = \begin{pmatrix} d^c \\ \ell \end{pmatrix}, \quad 10 = \begin{pmatrix} u^c & Q \\ Q & e^c \end{pmatrix}$$

$Y_e \neq Y_d$ →

$$\bar{5}' = \begin{pmatrix} D^c \\ L \end{pmatrix}, \quad 5' = \begin{pmatrix} D \\ L^c \end{pmatrix}$$

$M_\nu \neq 0$ →

$$24 = \begin{pmatrix} \rho_8 & \rho_{(3,2)} \\ \rho_{(\bar{3},2)} & \rho_3 \end{pmatrix} + \lambda_{24} \rho_0$$

$$M_{\rho_8} = \hat{m}_{24} M_{\rho_3}, \quad M_{\rho_0} = \frac{1}{5}(3 + 2\,\hat{m}_{24}) M_{\rho_3}, \quad M_{\rho_{(3,2)}} = M_{\rho_{(\bar{3},2)}} = \frac{1}{2}(1 + \hat{m}_{24}) M_{\rho_3}.$$

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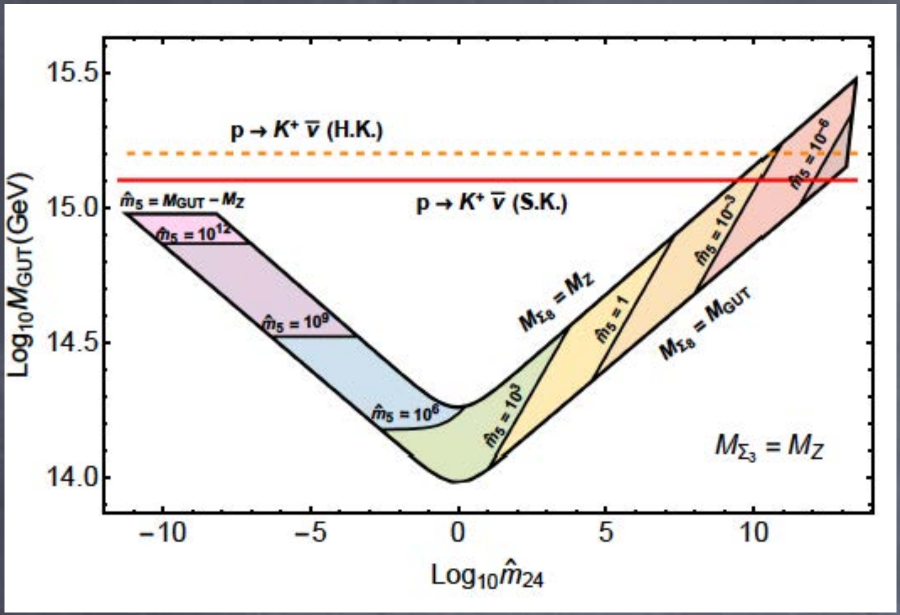
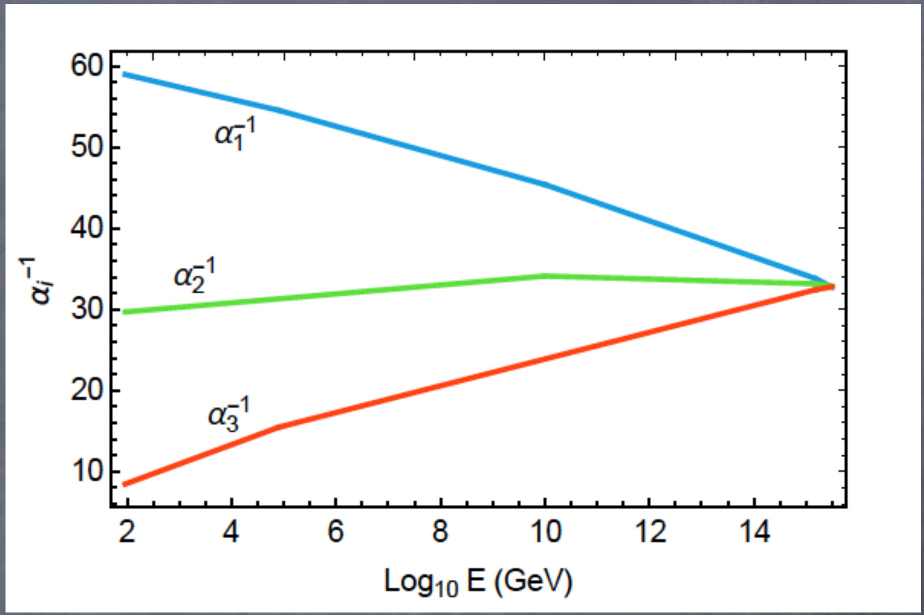
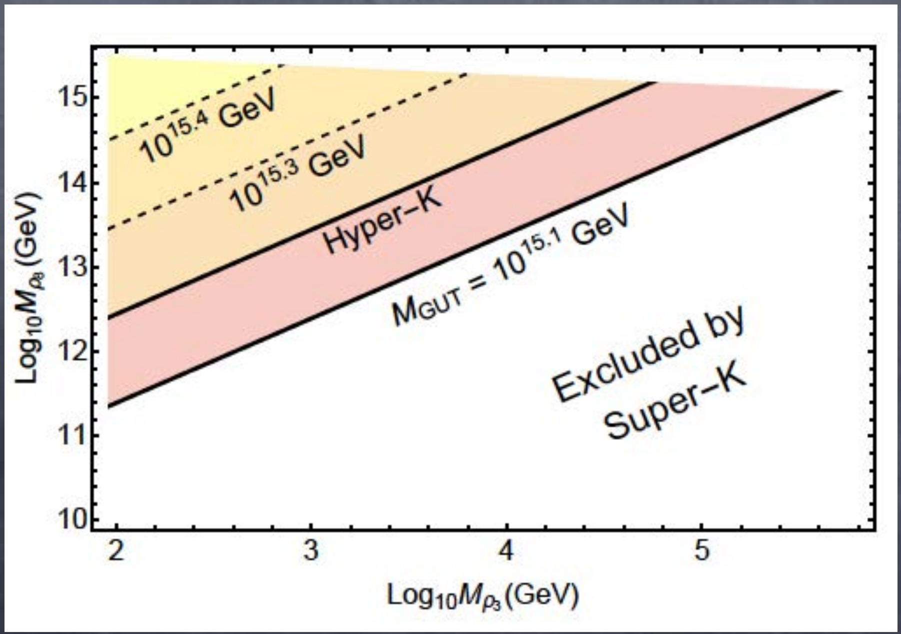
Realistic SU(5) Grand Unified Theory







$$M_{\rho 3} \leq 500 \text{ TeV}$$

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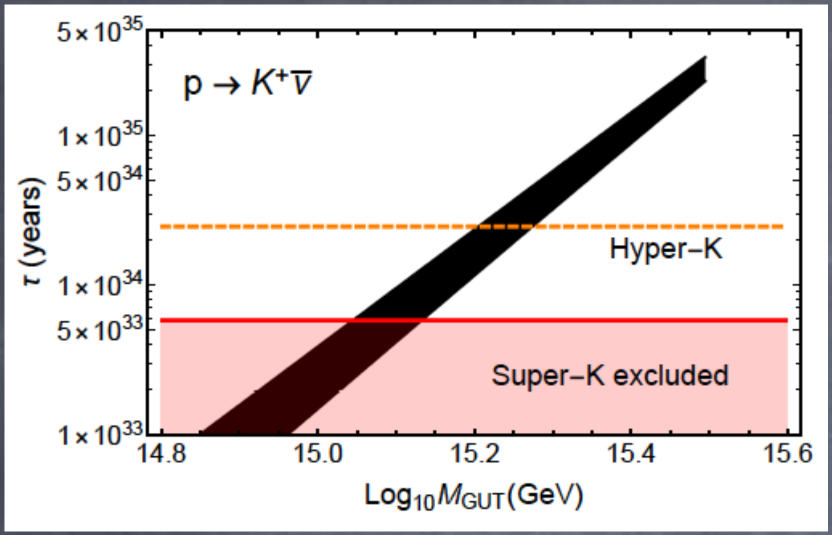
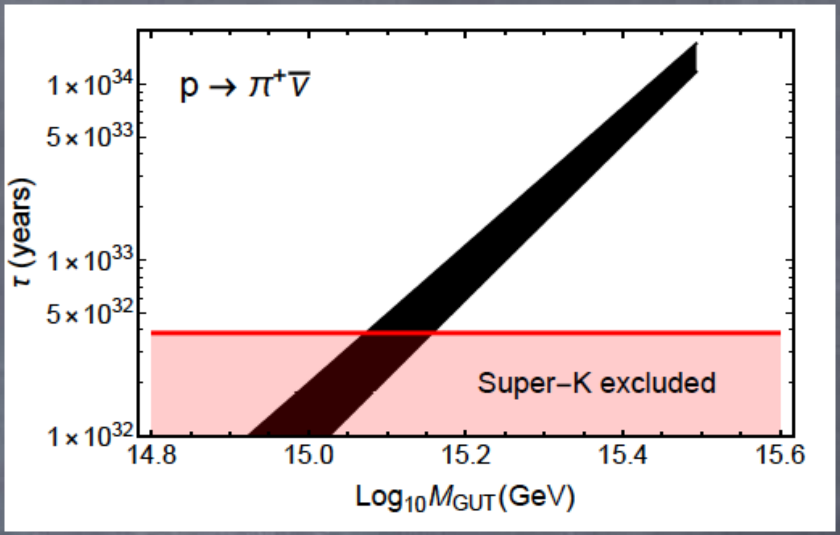
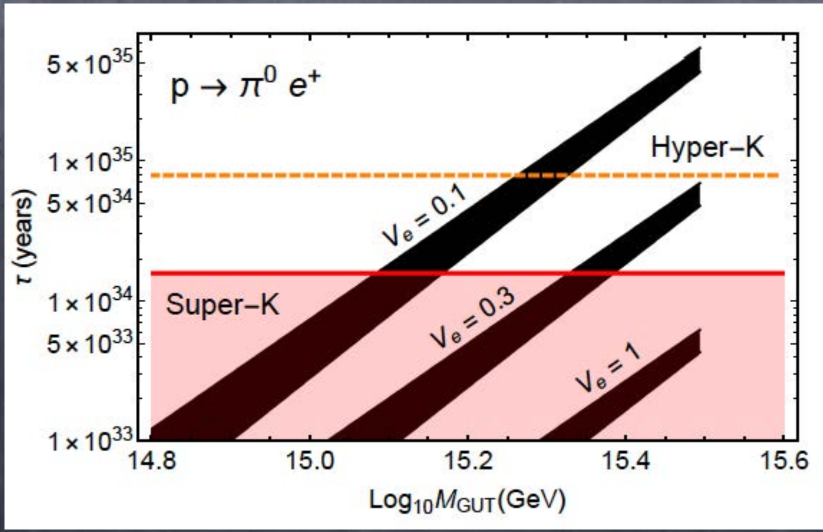
Realistic SU(5) Grand Unified Theory





$$\tau(p \to K^+\bar{\nu}) \lesssim 3.4 \times 10^{35} \text{ and } \tau(p \to \pi^+\bar{\nu}) \lesssim 1.7 \times 10^{34} \text{ years.}$$



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SUMMARY

The testability of the theory of neutrino masses is crucial to complete our understanding of the origin of fermion masses !

I have presented strong motivations for the realization of the seesaw mechanics at the multi-TeV scale and to look for lepton number violation at the LHC or future colliders.

The Seesaw Scale must be in the multi-TeV scale in the simplest theories based on B-L if there is a relation between DM and the origin of neutrino masses.

The minimal supersymmetric theory based on B-L predicts that lepton number must be broken at the SUSY scale. Therefore, if SUSY is realized at the multi-TeV scale one could test the origin of neutrino masses at colliders.

We have discussed a simple renormalizable SU(5) grand unified theory which predicts an upper bound on the proton decay lifetime and can be probed at the SK or HK. We predict an upper bound on the Type III seesaw field mass in the multi-TeV scale.

Thank You !

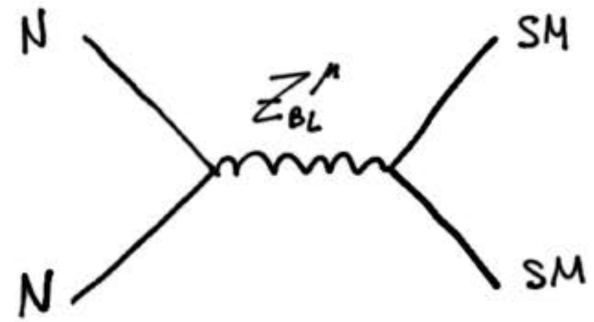
Extra Information

P. F. P., C. Murgui, Phys. Lett. B777 (2018) 381

Light sterile neutrinos and Cosmological bounds

- Annihilation rate:

$$\Gamma_N(T) = n_N(T) \sum_f \langle \sigma_f(NN \to \bar{f}f) v \rangle$$



- Annihilation cross-section:

$$\sigma_f(s) = \frac{g_{BL}^4}{12\pi} \frac{N_c^f (Q_{BL}^f)^2 s}{\left[(s - M_{Z_{BL}}^2)^2 + M_{Z_{BL}}^2 \Gamma_{Z_{BL}}^2\right]},$$

$$\Rightarrow \boxed{\Gamma_N(T) = \frac{49\pi^5 T^5}{194400\, \xi(3)} \left(\frac{g_{BL}}{M_{Z_{BL}}}\right)^4 \sum_f Q_{BL}^f N_c^f}$$

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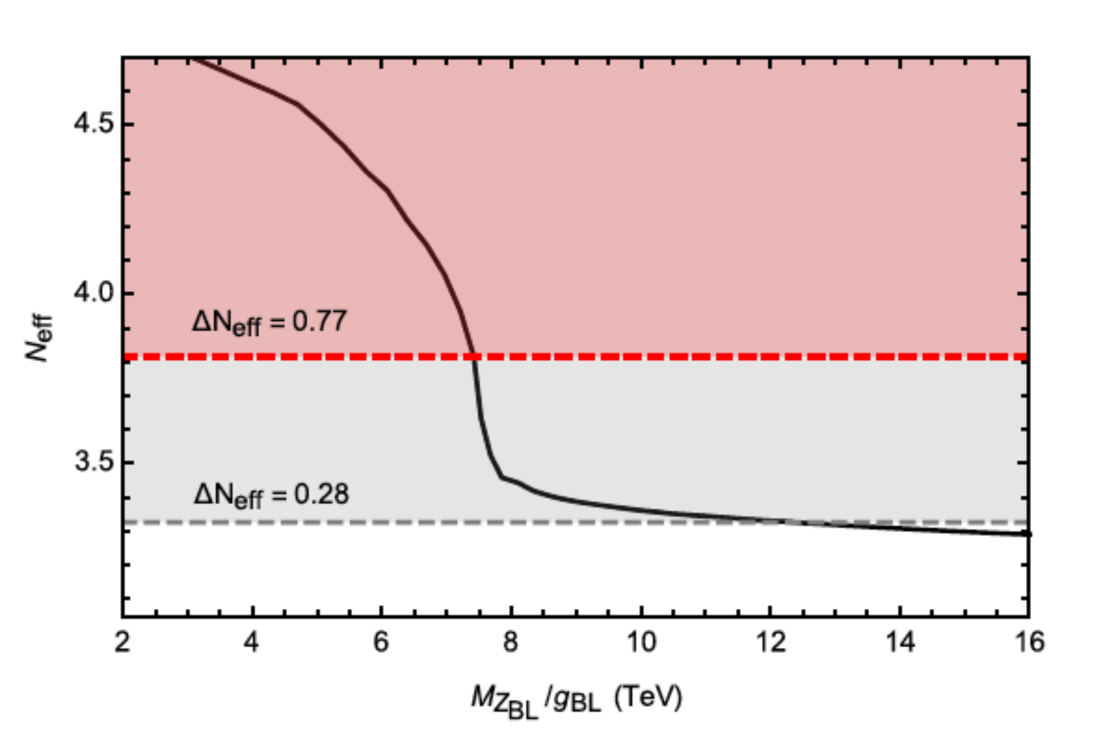
Light sterile neutrinos and Cosmological bounds

$$\Delta N_{eff} < 0.28 \text{ when } H_0 = 68.7^{+0.6}_{-0.7}\ \text{Mpc}^{-1}\ \text{km/s},$$
$$\Delta N_{eff} < 0.77 \text{ when } H_0 = 71.3^{+1.9}_{-2.2}\ \text{Mpc}^{-1}\ \text{km/s}.$$



$$\frac{M_{g_{BL}}}{g_{BL}} > 7\ \text{TeV}(\text{LEP2})$$

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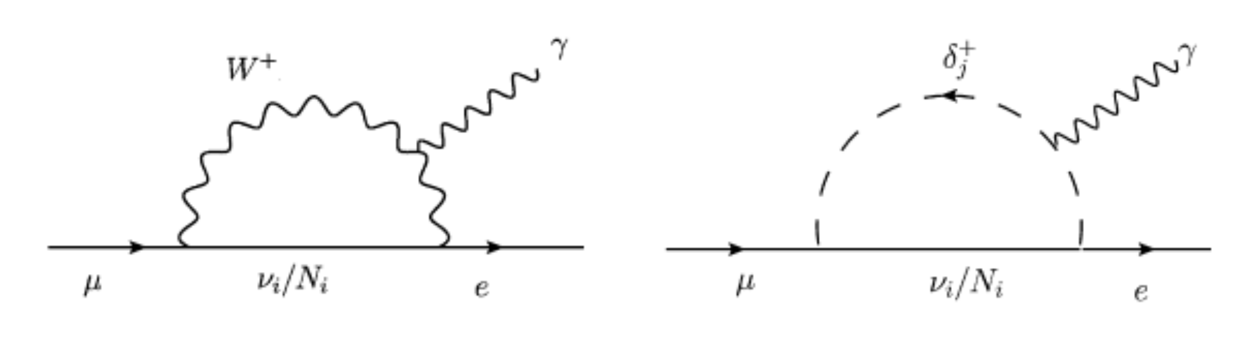
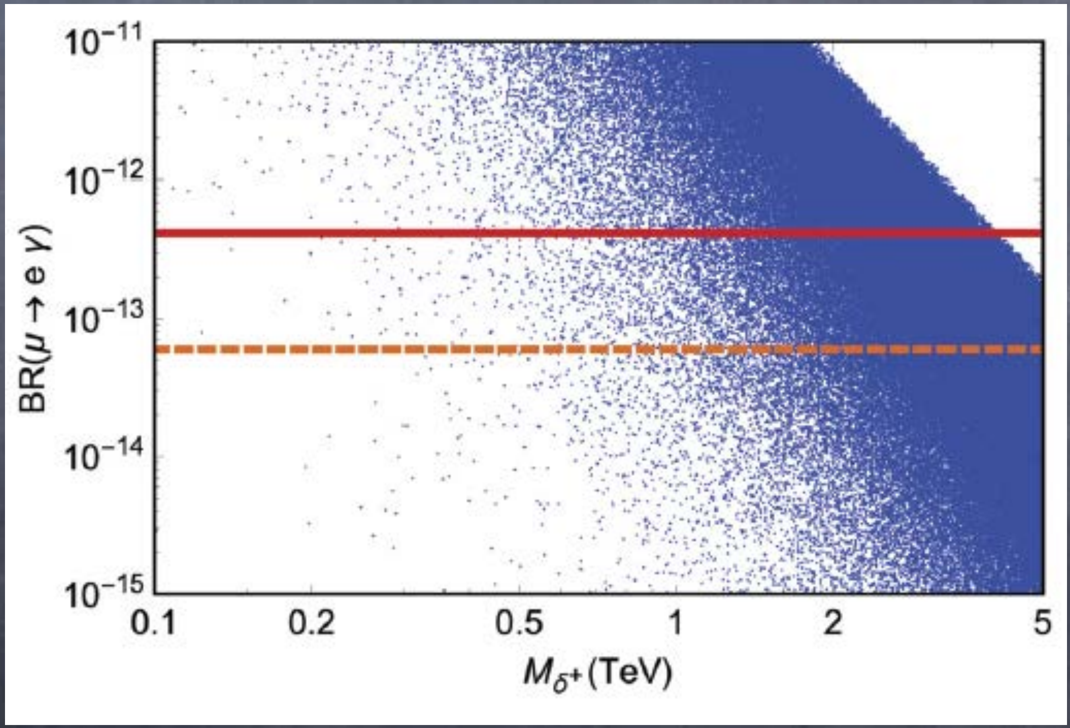
Possible Large Contributions to LFV processes

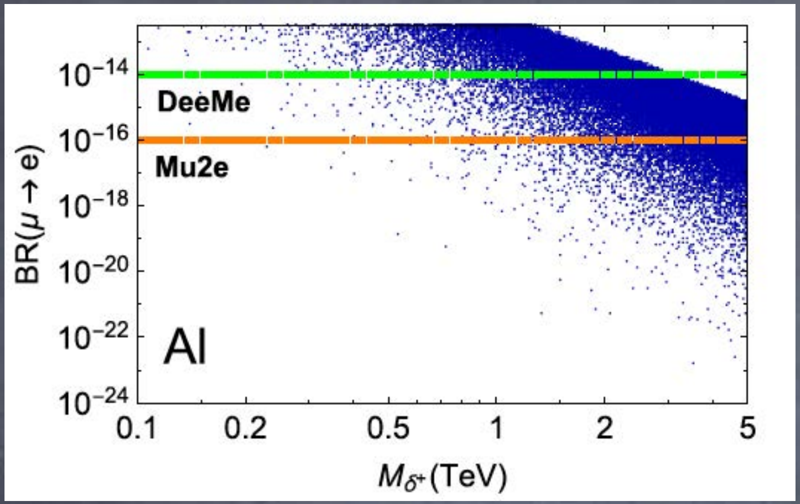


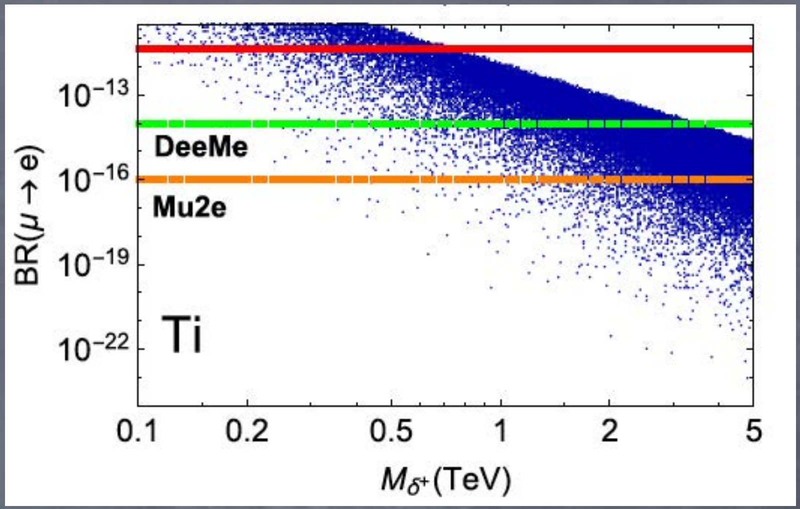


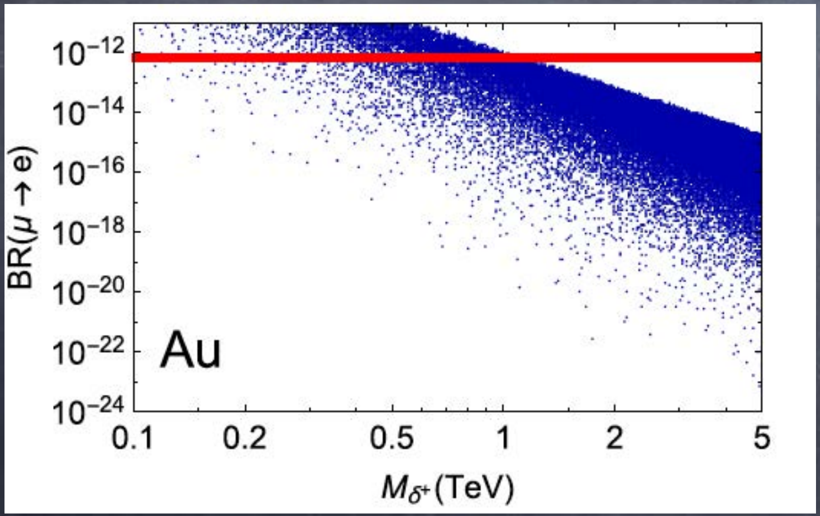
P. Fileviez Perez

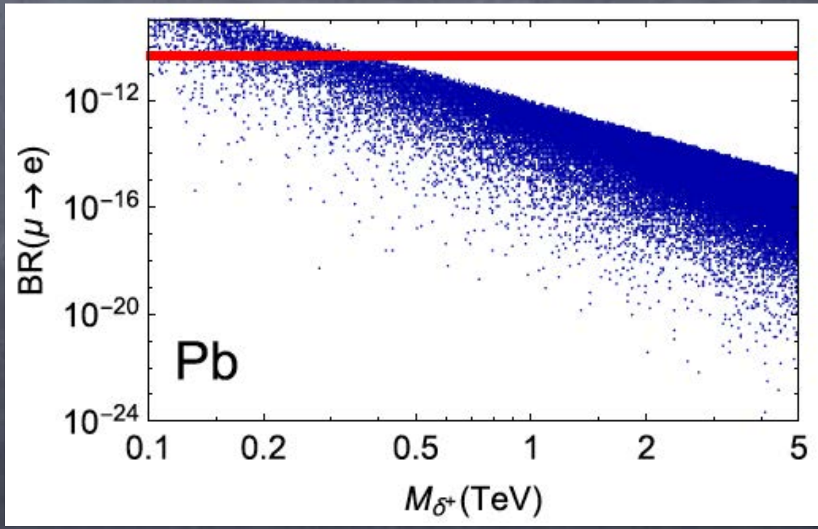
P. F. P., C. Murgui, Phys. Lett. B777 (2018) 381

Possible Large Contributions to LFV processes









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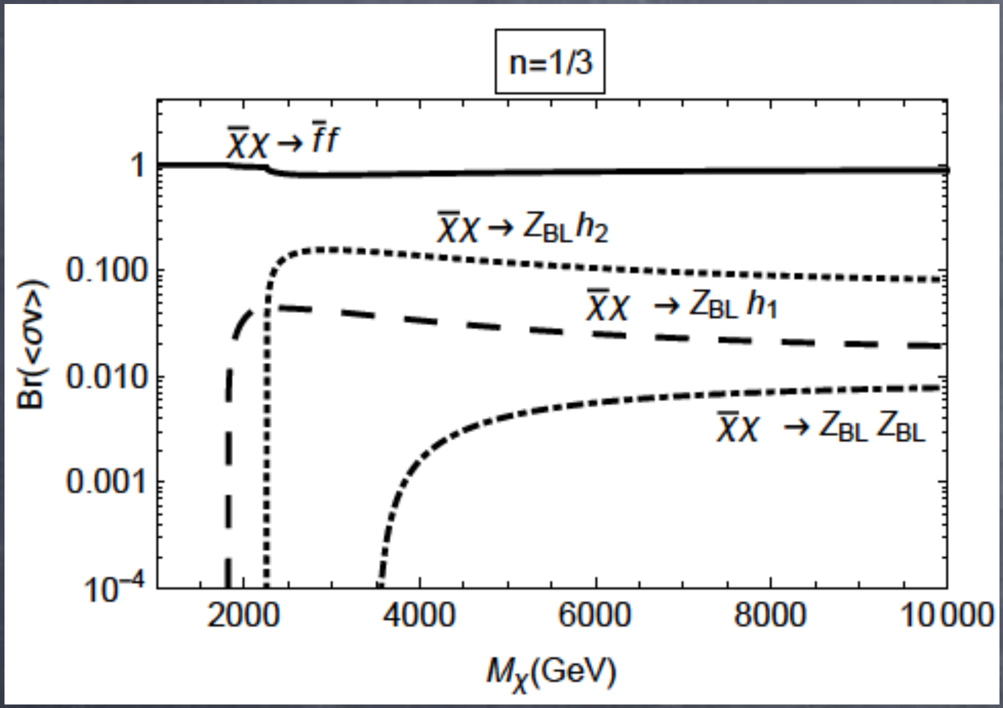
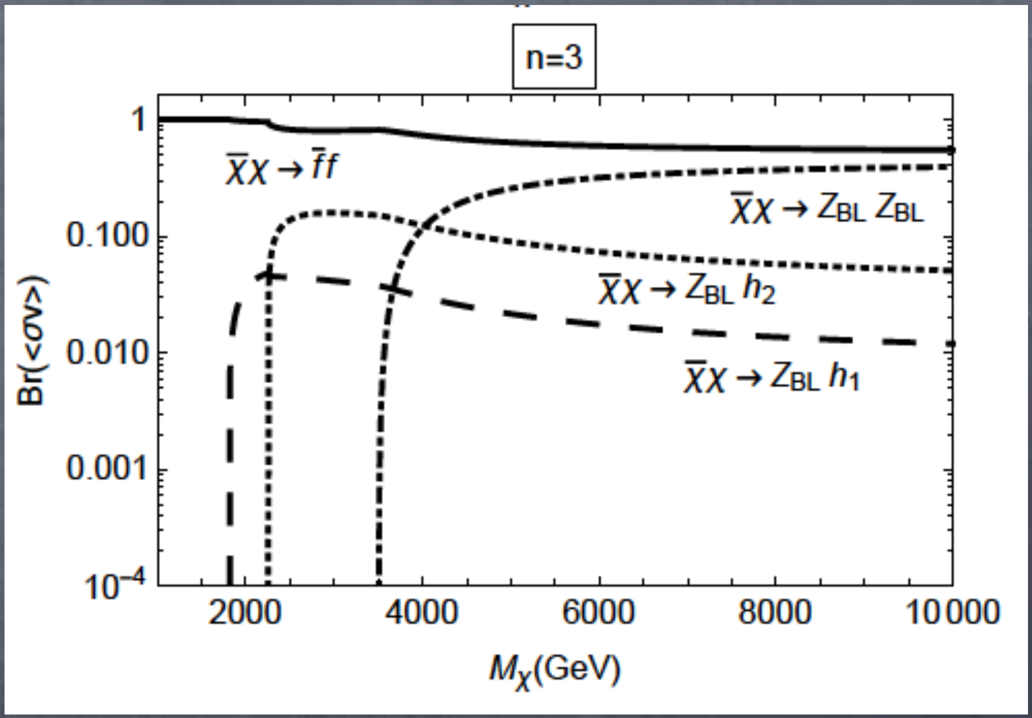
P. F. P., C. Murgui, arXiv:1803.07462

Seesaw Scale and Dark Matter





P. F. P., C. Murgui, arXiv:1803.07462

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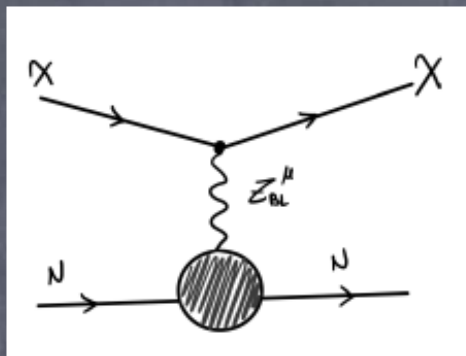
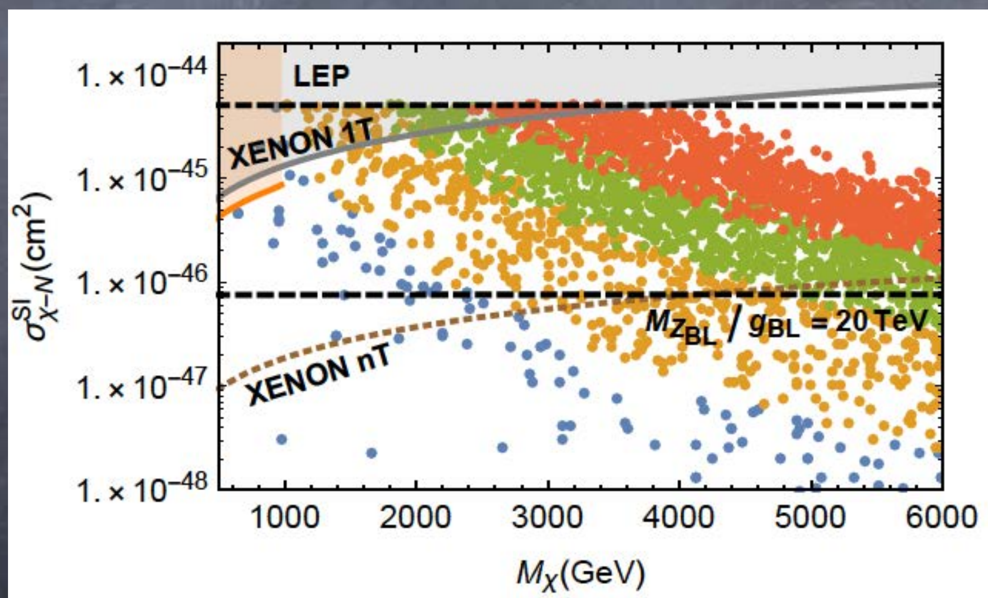


$$\sigma_{\chi N}^{SI} = \frac{M_N^2 M_\chi^2}{\pi (M_N + M_\chi)^2} \frac{g_{BL}^4}{M_{Z_{BL}}^4} n^2$$



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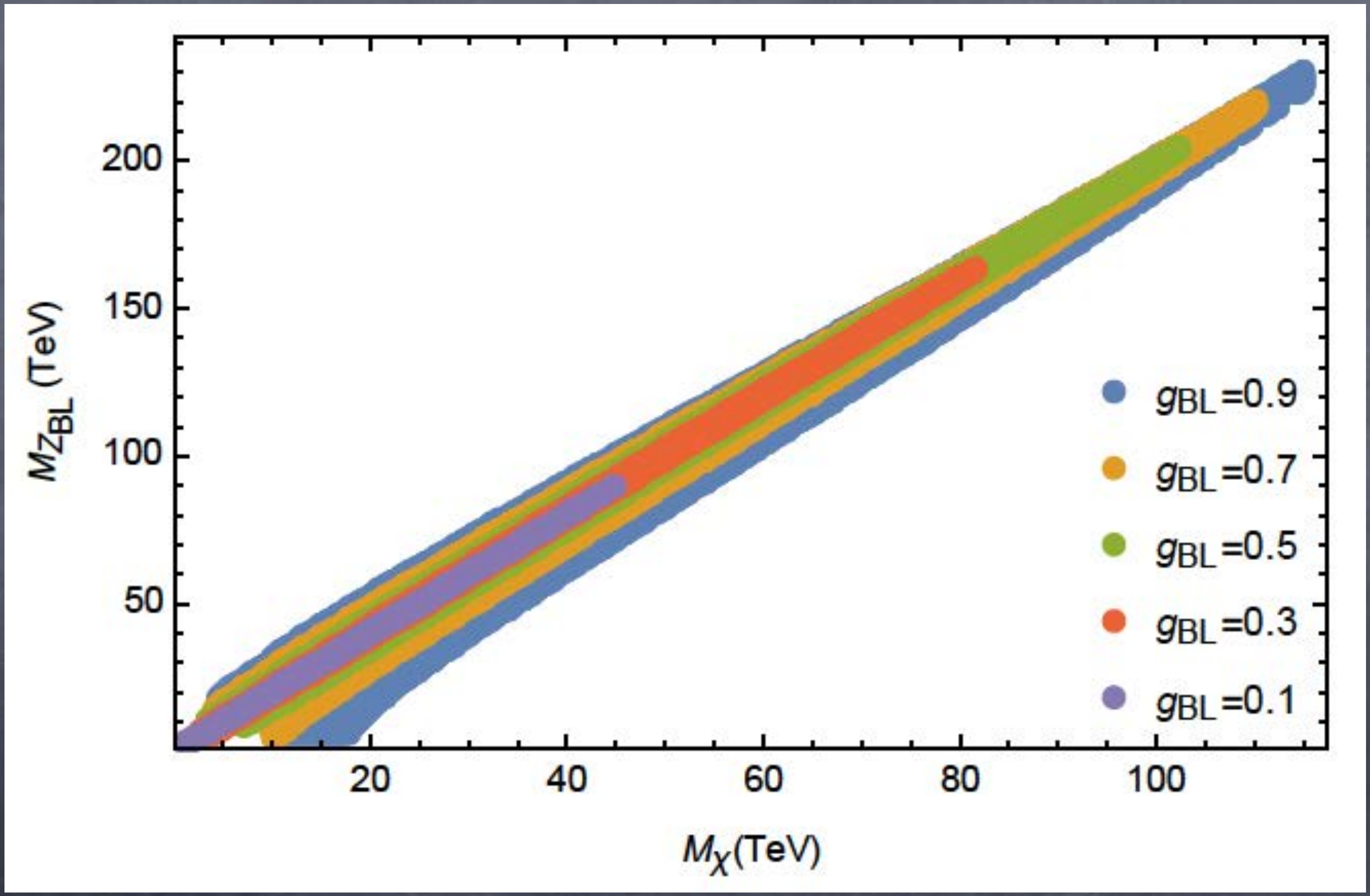
Seesaw Scale and Dark Matter

$n = 3$ when $\Omega_{DM} h^2 \leq 0.1199 \pm 0.0027$



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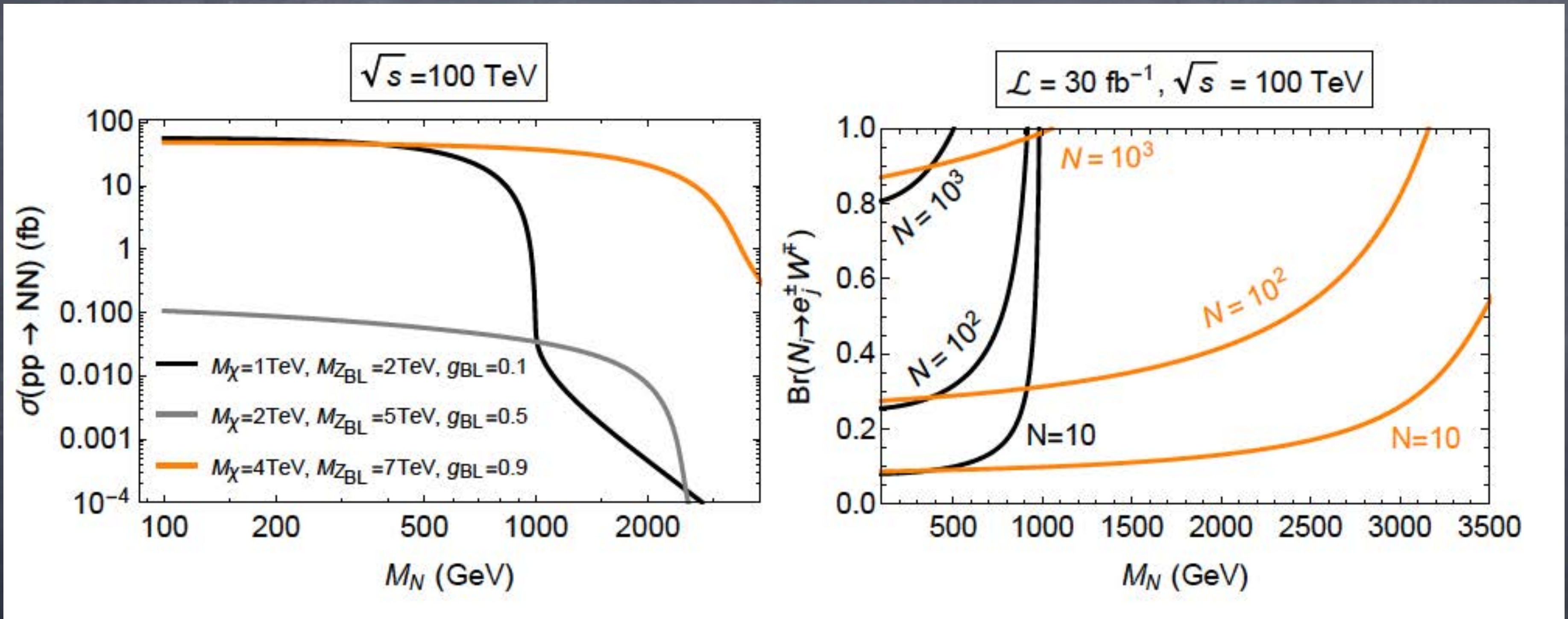
Testability at Future Colliders

$$pp \to Z^*_{BL} \to N_i N_i \to e^\pm_j W^\mp e^\pm_k W^\mp \to e^\pm_j e^\pm_k 4j.$$



P. Fileviez Perez

What is the origin of the tachyonic mass for $\tilde{\nu}^c$?

a) $f \nu^c \nu^c X$ ⇒ Radiative Symmetry Breaking

P. F. P., Spinner, 2010

b) $S^{'} = \mathrm{Tr}\left(\mathrm{Y_{B-L}} \tilde{\mathrm{m}}^2\right) \neq 0$ at GUT scale

M. Ambroso, B.A. Ovrut, 2009, 2010